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# Error-Free 320 Gb/s Simultaneous Add-Drop Multiplexing

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**Abstract:** We report on the first demonstration of error-free time-division add-drop multiplexing at 320 Gb/s. The add- and drop-operations are performed simultaneously in a non-linear optical loop mirror with only 100 m of highly non-linear fibre.

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## 1. Introduction

Optical Time-Division Multiplexing (OTDM) is the technique where a number of low bit rate data channels at identical wavelengths are bit-interleaved in order to generate a high bit rate data signal. Time-division add-drop multiplexing (ADM) is an important network functionality where a data-channel is extracted (drop) from the composite OTDM signal, and then replaced by a new data-channel (add) [1,2,3]. We have previously demonstrated that these two operations (add and drop) can be performed simultaneously at 80 Gb/s in a non-linear optical loop mirror (NOLM) [4].

Previous attempts at 320 Gb/s add-drop multiplexing included only eye-diagram characterisations of the performance [1,3]. Here, we use the principle of simultaneous ADM from [4] to realise the first demonstration of error-free 320 Gb/s add-drop multiplexing, with a full bit error rate evaluation. The experimental set-up is improved compared to [4], with only 100 m of highly non-linear fibre in the NOLM, and there is no extra penalty from the add-operation.

## 2. Principle

The principle of simultaneous add-drop multiplexing in a NOLM, denoted sADM, is shown in Figure 1. It is essentially based on cross-phase modulation (XPM) between a high-intensity control pulse-train and two data-channels inside the highly non-linear fibre (HNLF) in the loop. The two data-channels are the add-channel and the target drop-channel, which is the channel in the 320 Gb/s OTDM signal that is targeted to be dropped.

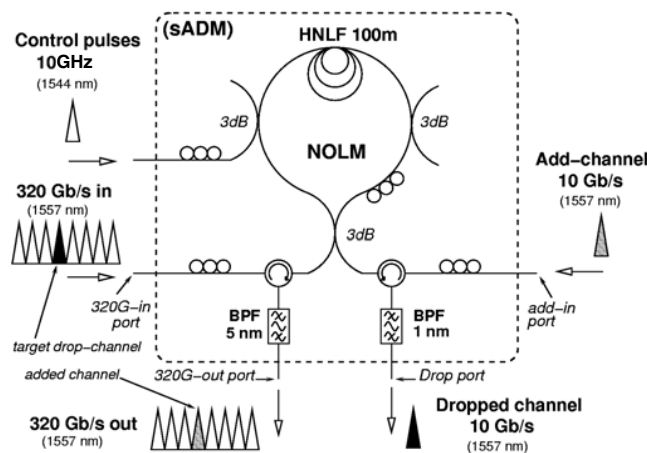


Figure 1. Principle of simultaneous add-drop multiplexing in a NOLM (sADM).

The input data signals to the sADM are the 320 Gb/s OTDM signal (left), composed of 32 bit-interleaved 10 Gb/s channels, and the 10 Gb/s add-channel (right), both at 1557 nm. The internal polarisation control of the

NOLM is set such that these signals are both reflected from the loop. The 10 GHz control pulses (at 1544 nm) are then coupled into the loop and are simultaneously synchronised with the clockwise-propagating components of both the target drop-channel and the add-channel inside the HNLF. Because of the XPM-induced phase-shifts, the target drop-channel is switched to the drop-port, and the add-channel is switched to the 320G-out port into the bit-slot left by the dropped channel. The control pulses are filtered out by optical bandpass filters (BPF) after the circulators. The time-width and power of the control pulses, as well as the polarisation states of the different signals, are all adjusted in order to optimise the switching extinction ratio for the data-pulses. This minimises the interferometric cross-talk experienced by both the added channel and the dropped channel because of time-overlap with non-switched light (the added channel overlaps with non-switched drop-channel light, and the dropped channel with non-switched add-channel light).

### 3. Experimental set-up

The experimental set-up is shown in Figure 2.

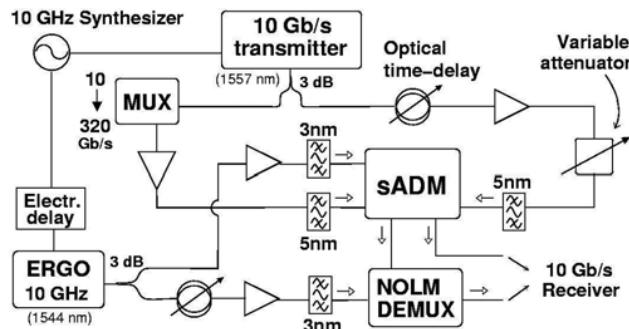


Figure 2. Experimental set-up.

The 10 Gb/s transmitter contains a 10 GHz Erbium Glass Oscillator pulse generating laser (ERGO) at 1557 nm, and a Mach-Zender modulator, which amplitude-modulates the pulses with a  $2^7-1$  PRBS data pattern. One 3 dB output of the 10 Gb/s transmitter is multiplexed up to single polarisation 320 Gb/s by a passive  $2^7-1$  PRBS-maintaining delay-line multiplexer (MUX). The other 3 dB output is used as the 10 Gb/s add-channel input to the sADM (the in/out ports are placed as shown in Figure 1). Another 10 GHz ERGO at 1544 nm (ERGO) is used to generate control pulses for both the sADM and another NOLM (NOLM DEMUX, with 200 m HNLF), used for demultiplexing the 320 Gb/s output of the sADM, allowing a full bit error rate (BER) evaluation of the signal. The dropped channel and the demultiplexed channels from the NOLM DEMUX are sent to the 10 Gb/s receiver. A 10 GHz synthesizer synchronises the transmitter, the receiver, and the 1544 nm ERGO. The average powers and pulse widths (FWHM) at the input to the sADM are: 9.8 dBm and 1.6 ps for the 320 Gb/s pulses, -5.8 dBm and 1.6 ps for the add pulses, and 26.0 dBm and 2.6 ps for the control pulses. It is very important to have broader control pulses in order to switch all of the data-pulse. Compared to [4], the set-up has been optimised in a number of ways: the control pulse laser is an ERGO with low timing-jitter, the NOLM is loss-balanced with an extra 3 dB coupler, the HNLF is in a loose coil and the length is only 100 m (non-linear coefficient  $\gamma = 10.5 \text{ W}^{-1}\text{km}^{-1}$ , zero-dispersion wavelength 1554 nm, dispersion slope  $0.018 \text{ ps}\cdot\text{nm}^{-2}\cdot\text{km}^{-1}$ ).

### 4. Results

The simultaneous add-drop operation of the sADM at 320 Gb/s is successful with error-free performance, as shown in Figures 3 and 4.

Figure 3 shows an eye diagram of the dropped channel as well as cross-correlation traces of the 320 Gb/s input and output data-signals of the sADM. The dropped channel in Figure 3 (a) is seen to have a clear and open eye. The cross-correlation traces in Figure 3 (b), (c) show that the added-channel has the same timing and approximately the same amplitude as the original channel (the target drop-channel). For illustration, Figure 3 (d) shows the 320 Gb/s sADM output in the case where the add-channel is turned off. It is seen that the sADM has cleared the bit-slot occupied by the target drop-channel in the 320 Gb/s sADM input.

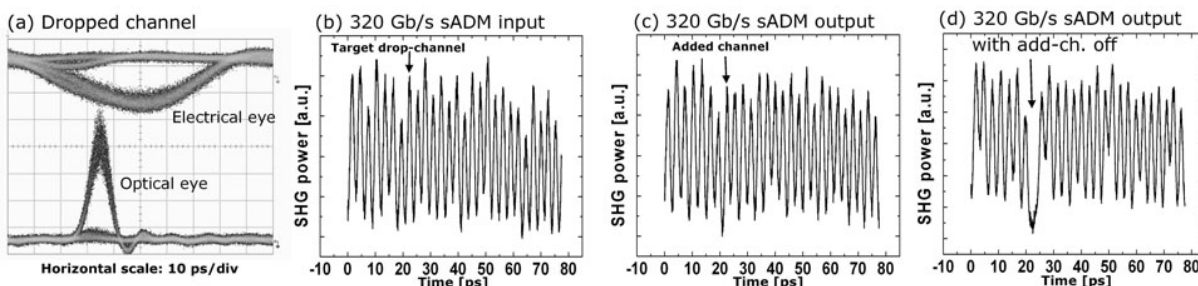


Figure 3. Oscilloscope eye diagrams of the dropped channel (a), and cross-correlation traces of the 320 Gb/s input and output signals of the sADM, obtained with a 800 fs sampling pulse (b, c, d). Note that graphs (b), (c) and (d) only display the top of the cross-correlation traces. The amplitudes of all channels in the 320 Gb/s signal are nearly identical.

Figure 4 shows the BER measurements. The dropped channel has a sensitivity of -34.5 dBm (penalty 2 dB compared to the 10 Gb/s B2B). If the add-channel input to the sADM is turned off, this sensitivity is measured to -34.6 dBm, which shows that the effect of the simultaneous add-operation on the drop-operation is negligible. All 32 channels of the 320 Gb/s sADM output are demultiplexed in two cases: 1) when the sADM control pulses are on, resulting in the add-drop operation explained above (black triangles in Figure 4), and 2) when the sADM control pulses are off, which results in total reflection of the 320 Gb/s input towards the NOLM DEMUX (denoted through-channels in Figure 4, empty triangles). These BER measurements show that the add-operation introduces only negligible penalty: after demultiplexing in the NOLM DEMUX, the added channel has pretty much the same sensitivity (-35.5 dBm) as the original channel, the target drop-channel (-35.3 dBm) (see Figure 4, left). This corresponds to a penalty of only ~1 dB compared to the 10 Gb/s back to back (B2B) sensitivity of -36.5 dBm (empty squares).

The sensitivities of all demultiplexed channels are shown in Figure 4, right. In case 1), the average sensitivity is  $-35.5 \pm 0.6$  dBm (black triangles), and in case 2), it is  $-35.4 \pm 0.5$  dBm (empty triangles). This shows that the sADM operation does not deteriorate the OTDM signal as a whole. We believe that the small variations observed in Figure 4 (right) are due to drifts in the time-delays inside the different stages of the multiplexer.

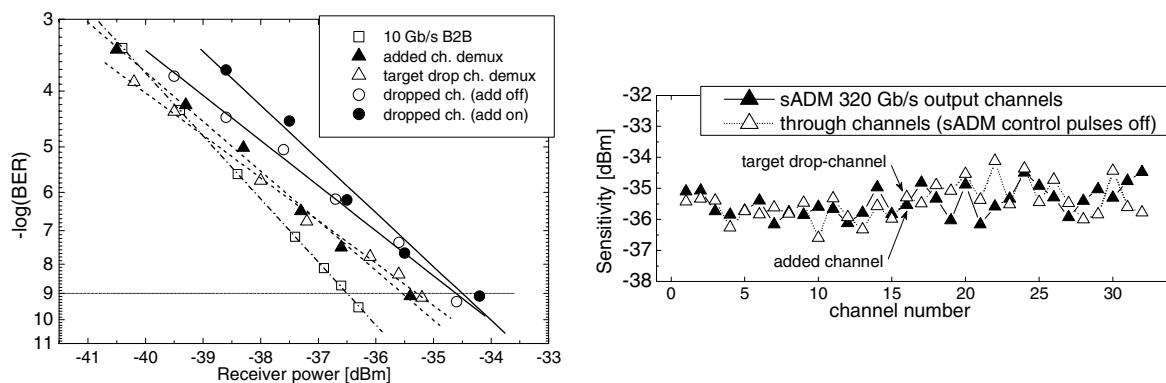


Figure 4. Bit error rate curves (left), and demultiplexed channel sensitivities (right).

## 5. Conclusion

We have reported on the first full BER evaluation of a 320 Gb/s add-drop experiment. For the first time, we demonstrate error-free time-division add-drop multiplexing at 320 Gb/s, by using a principle of simultaneous add-and-drop-operation in a NOLM with only 100 m HNLF. The add-operation introduces negligible penalty, and has a minimal effect on the drop-operation.

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